REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
04/30/97

3. REPORT TYPE AND DATES COVERED
Final Report 04/01/94 - 03/31/97

4. TITLE AND SUBTITLE
Research Investigation Directed Toward Extending the Useful Range of the Electromagnetic Spectrum

5. FUNDING NUMBERS
DAAL04-94-G-0057

6. AUTHOR(S)
Professor George W. Flynn

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Trustees of Columbia University in the City of New York
Box 20, Low Memorial Library
New York, New York 10027

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
4300 South Miami Blvd., P.O. Box 12211
Research Triangle Park, North Carolina 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 32413.30-EL-JSEP

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The research performed under this contract is described in the attached report. Included are the Director's Overview, degrees awarded, publications and inventions. Principal Investigators for this research period were B.E. Bent, G. W. Flynn, I.P. Herman, R.M. Osgood, M. C. Teich and E. S. Yang.

14. SUBJECT TERMS

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

CRL

COLUMBIA UNIVERSITY

JOINT SERVICES ELECTRONICS PROGRAM
FINAL REPORT

RESEARCH INVESTIGATION DIRECTED TOWARD EXTENDING THE USEFUL RANGE OF THE ELECTROMAGNETIC SPECTRUM

Contract DAAL04-94-G-0057
For the Period April 1, 1994 - March 31, 1997

Presented to:

THE JOINT SERVICES TECHNICAL ADVISORY COMMITTEE
Representing: THE U.S. ARMY RESEARCH OFFICE,
THE OFFICE OF NAVAL RESEARCH,
and THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Submitted and Prepared by:

COLUMBIA RADIATION LABORATORY
DEPARTMENTS OF CHEMISTRY, APPLIED PHYSICS,
AND ELECTRICAL ENGINEERING
COLUMBIA UNIVERSITY in the City of New York
NEW YORK, NEW YORK 10027

April 30, 1997

JSEP FINAL REPORT

Grant DAAH04-94-G-0057

Period: April 1, 1994 - March 31, 1997

CONTENTS

A. PRINCIPAL INVESTIGATORS

B. E. Bent
G. W. Flynn
I. P. Herman
R. M. Osgood
M. C. Teich
E. S. Yang

B. OVERVIEW

Experimental counting distributions and interevent-time histograms for photon detection were obtained by Professor M. C. Teich's group from spontaneous parametric downconversion, both marginally and as coincidences. The experiments were conducted with a $LiIO_3$ downconverter pumped by 413-nm Kr^+-ion laser light. The data are consistent with Poisson statistics; a model leading to this result was presented. This result is highly useful in the course of using parametric downconversion for applications such as ranging and quantum cryptography. Theoretical and experimental second- and fourth-order interference patterns were obtained for entangled photons of different colors entering single and dual Mach-Zehnder interferometers (MZIs) in which dispersive elements were deliberately placed. Professor Teich's group showed that pump-frequency oscillations are present in the coincidence rate patterns for arbitrarily long path-length-difference times, confirming the robustness of this nonlocal phenomenon in the presence of dispersion. A multidimensional Gaussian approximation of the wave function for the signal and idler light generated by spontaneous parametric downconversion was used to derive analytical expressions for the second-order coherence function and the fourth-order coherence function (which is proportional to the signal-idler photon coincidence rate). In another domain, techniques were further developed for estimating fractal exponents for stochastic point processes. Two wavelet-based measures suitable for exponent estimation were defined: the wavelet Fano factor (WFF) and the wavelet Allan factor (WAF). These arise as natural generalizations of two simple count-based measures: the Fano factor (FF) and Allan factor (AF), respectively. As a result, wavelet-based measures can be fruitfully added to our armamentarium of techniques for estimating the fractal exponent of an FSPP. Finally, progress was also achieved in developing a coherent sub-carrier fiber-optic communication system with phase-noise cancellation.

Important advances were made by Professor I. Herman's group in the understanding of how strain affects properties of semiconductors and their heterostructures. In one example, how hydrostatic strain modifies optical emission from bulk Si and SiGe/Si heterostructures and superlattices that are isoelectronically doped by Be pairs was examined experimentally and modeled using the HTL model to analyze exciton binding. Recombination leading to the I_2, donor-acceptor pair line, and "yellow band" photoluminescence features in wurtzite GaN epilayers under hydrostatic pressure was also examined. A powerful modified bond-charge model was developed that comprehensively describes all the effects of strain on the elastic properties of partially ionic semiconductors, such as Group III-V and II-VI structures, and gives phonon frequencies under any type of strain, even for confined phonons. Another part of the work unit included a collaboration with Professor Bent using optical spectroscopy to monitor surface-related properties during novel dry etching methods in GaAs. Monitoring the surface during growth and etching can improve the understanding of how surfaces can be modified for improved interfacial properties. To support this work, the dielectric functions of the surface layers of GaAs were analyzed for use in *in situ* surface photoabsorption studies. Theoretical studies also included the *ab initio* analysis of the reconstruction, electronic structure, and the optical properties of several reconstructions of the GaAs(001) surface.

The physics of electrons at interfaces or surfaces are crucial for the operation of many forms of advanced devices. Such surface electrons have been studied by Professor Osgood's

group using non-linear photoemission. The implementation of a series of significant upgrades in his nonlinear photoemission experimental apparatus made possible the utilization of the angle-resolved two-photon photoemission technique to extensively investigate the dynamics of the two-dimensional electrons at single-crystal copper surfaces upon introduction of small amounts of impurity atoms. The results demonstrated that the scattering caused weakened conservation of the parallel momentum due to quantum confinement. A phenomenological absorption scattering cross-section was introduced to characterize this non-lifetime linewidth broadening mechanism. In addition, the rate of inelastic scattering of the electrons moving parallel to the surface was measured for the first time.

Angle-resolved *resonant* 2PPE measurements were made to study height-dependent electronic structures on regularly stepped single-crystal surfaces by probing three different surface states simultaneously. Electron confinement effects due to nanoscale steps were observed for electrons within 1nm from the steps. Reduced-dimensionality, quantum confinement was observed for electrons on nanostructured metal surfaces. Lateral superlattice effects were observed for the first time using electrons on a stepped Cu(001) surface via angle-resolved two-photon photoemission. Adsorption of Na atoms (~0.01 ML) on the stepped surface enhanced the step regularity, yielding clear zone-folding with a reduced Brillouin zone given by the reciprocal step lattice. A new femtosecond mode-locked Ti:Sapphire laser system and its diagnostic accessories were installed and refined with good laser output properties. Further extension of the laser photon energy to the UV range was setup with second and third harmonic generation.

In a separate experiment a new low-damage, high resolution optically initiated etching technique was applied to the fabrication of quantum-box-like structures. The electronic quality of these structures was studied using photoluminescence. Comparison of the luminescence efficiency of these structures to the luminescence efficiency of similar structures fabricated using wet etching, indicated that this new etching technique induced little or no damage to the sample. The luminescence behavior of samples with lateral feature sizes as small as 100 nm was modeled. In a separate experiment, deep-etch-defined $GaAs/Al_{0.3}Ga_{0.7}As$ square features of multiquantum well material, with dimensions as small as 160 nm, were fabricated using magnetron reactive ion etching (MIE). Luminescence spectroscopy showed confinement of charge carriers at the features' center. The effects of rf power and etching time on the luminescence efficiency of these features and its concomitant etch-induced damage were examined. Cathodoluminescence was also employed to investigate the luminescence and lateral transport properties of excited carriers at 8K in this same etched material. The effect of feature size on luminescence efficiency was examined and compared with model calculations. Finally, in a collaboration with Professor Flynn, carbon nanotubes were used in atomic force microscopy to examine the morphology of nanometer sized features fabricated with magnetron enhanced reactive ion etching.

Research of Professor Flynn's group resulted in significant progress in the development of Scanning Tunneling Microscope (STM) techniques for determining the structure of long chain molecules adsorbed on solid surfaces. The packing of short polymer molecules on graphite surfaces using STM was investigated for a number of different systems. STM images of alcohols (R-OH, 1-docosanol), alkanethiols (R-SH, 1-docosane thiol), alkyl chlorides (R-C1, 1-chlorooctadecane), and alkyldisulfides (R-S-S-R, docosane disulfide) on graphite were compared. The alkyl chlorides were compared with the alkanethiols. The alkyldisulfides were investigated to determine if placement of S atoms in different positions in the alkyl chains affected the STM images. The effect of the SH group on both the contrast and orientation of molecules observed in the STM images was remarkable. STM images of alkanethiols under phenyloctane solvent on graphite indicated that the tunneling current near the thiol functional group was dramatically enhanced compared to that of the methylene groups in the hydrocarbon chain. This contrast allows the position of the thiol functional group to be located in a molecule adsorbed on a surface. Images of the alkyl disulfides revealed bright spots corresponding to the position of the S-S groups. Several chemical functional groups were found to be exceptionally "bright" in the STM suggesting their use as markers for a variety of applications in nanotechnology and materials science. A simple, preliminary model was developed that successfully explained the observed high tunneling

current for these functional groups and suggested a number of well posed tests to determine the general applicability of the model to a wide range of surface adsorbates. Long chain hydrocarbons with bromine atom end groups were found to exhibit novel behavior in which the bromine end of the molecule alternates between dark and bright STM images over a period of approximately 10 minutes.

A collaboration between Columbia University and Fort Monmouth Army Research Center, involved the development of magnetron enhanced reactive ion etching (MIE) as a method for fabricating 30 nm features in GaAs. Atomic Force Microscopy (AFM) was used as a probe of both etch quality and sample damage, allowing a determination of optimal etch conditions. Efforts were made to compare the utility of commercially available, sharpened silicon and silicon nitride tips with carbon nanotube tips. AFM studies of the etching of 100-200 nm lines and boxes indicated that use of high powers for carefully controlled etch periods as well as the use of high quality masks are necessary for optimal pattern formation. Extension of these studies to smaller (30 nm) GaAs etch features is currently underway. AFM studies of both the masks and GaAs etch samples are providing for the careful development of the MIE technique for the fabrication of 30 nm features necessary in the next generation of optoelectronic devices.

A new low temperature process using an electron cyclotron resonance (ECR) microwave plasma was developed by Professor E. Yang's group to grow (not deposit) a stoichiometric SiGe oxide directly on SiGe alloys. Both fully oxidized Si and Ge were achieved, and no Ge segregation occured at the oxide/SiGe interface or near the oxide surface. High quality 1 μm Al-gate SiGe pMOSFETs with ECR grown gate oxides were obtained with transconductance of 48 mS/mm (300 K) to 60 mS/mm (77 K). The low field hole channel mobility of the SiGe pMOSFETs was about a factor of two better than the corresponding silicon devices. The reported SiGe MOS transistors represented not only the first successfully grown SiGe gate-oxide, but the first MOS transistor with a grown gate-oxide in any compound semiconductor.

Carbon-doped GaInP/GaAs heterojunction bipolar transistors (HBT's) and heterostructure-emitter bipolar transistors (HEBT's) were fabricated and compared. It was shown that this HEBT offers a smaller offset voltage and better uniformity in DC characteristics across the wafer while RF performance of the HEBT is similar to that of HBT's. A maximum oscillation frequency (f_{max}) of 90 Ghz for an HEBT was obtained. Making use of a new structure with selective epitaxy, the collector capacitance of an HBT was reduced to about half that of a conventional HBT, and an f_{max} of 140 GHz was obtained.

Using CCl_4 doped InP as a buffer, a kink free GaInP/GaInAs/InP high electron mobility transistor (HEMT) was obtained with state-of-the-art transconductance of 420 mS/mm (300K) and 610 mS/mm (77K) and cutoff frequency of 15 Ghz. GaInP/GaAs HBTs and HEMTs were integrated for the first time, providing an ideal technology for the fabrication of the integrated front-end in microwave transceivers.

Research in Professor Bent's group focused on three problems important for atomic control of surface processing: (1) research in the layer-by-layer etching of GaAs(100) using atom-selective and atom-induced surface reactions to control the etch process demonstrated that HCl selectively etches Ga atoms from a GaAs surface in the temperature range 600-650 K; (2) research in the application of atoms and radicals to induce the carbon-carbon bond forming reactions required to produce organic films demonstrated that surface-generated free radicals can be harnessed to induce these reactions at cryogenic temperatures; and (3) research in the vibrational studies of silicon surfaces demonstrated that implantation of a conductive cobalt silicide layer beneath the silicon surface allows one to obtain (with synchrotron radiation) single reflection vibrational spectra of adsorbates on silicon at frequencies where bulk silicon is optically opaque. Professor Bent's group in collaboration with Professor Herman's group, showed that surface photoabsorption measurements could be used to monitor the digital etching of GaAs *in situ*. This was the first demonstration of the utility of this optical diagnostic for surface etching reactions.

Professor Bent's death occured during this contract period. His research projects have been continued by his colleagues in the JSEP program. Progress on these scientific efforts is reported in the other sections of this report.

C. DEGREES AWARDED

Burke, H. H., Ph.D. 1995
Eng., J., Jr., Ph.D
Eryigit, R., Ph.D. 1997
Freiler, M., Ph.D. 1995
Heneghan, C., Ph.D. 1995
Kim, S., Ph.D. 1996
Michaels, C., Ph.D., expected 1997
Miller, J., Ph.D., expected 1998
Ou, H-J., M. S. 1997
Paiella, R., M.S. 1993
Shih, M. C., Ph.D. 1994
Sui, Z., Ph.D. 1993
Tchikatilov, D., Ph.D. expected 1998
Teplyakov, A., Ph.D., 1996
Turcott, R. G., Ph.D. 1994
Xin, W., Ph.D 1996
Yang, Y. F., Ph.D. 1995
Zheng, L., Ph.D., 1994

D. PUBLICATIONS

S. B. Lowen and M. C. Teich, "Estimating the Dimension of a Fractal Point Process," Proc. SPIE 2036, 64-76 (1993).

W. C. Kwong, P. R. Prucnal, and M. C. Teich, "Coherent Subcarrier Fiber-Optic Communication Systems with Phase-Noise Cancellation," IEEE Trans. Commun. 42, 2208-2212 (1994).

M. C. Teich and S. B. Lowen, "Fractal Patterns in Auditory Nerve-Spike Trains," IEEE Eng. Med. Biol. Mag. 13, 197-202 (1994).

A. Joobeur, B. E. A. Saleh, and M. C. Teich, "Spatio-Temporal Coherence Properties of Entangled Light Beams Generated by Parametric Downconversion," Phys. Rev. A 50, 3349-3361 (1994).

T. S. Larchuk, M. C. Teich, and B. E. A. Saleh, "Statistics of Entangled-Photon Coincidences in Parametric Downconversion," Ann. N.Y. Acad. Sci. 755 (Fundamental Problems in Quantum Theory), 680-686 (1995).

T. S. Larchuk, M. C. Teich, and B. E. A. Saleh, "Nonlocal Cancellation of Dispersive Broadening in Mach-Zehnder Interferometers," Phys. Rev. A 52, 4145-4154 (1995).

S. B. Lowen and M. C. Teich, "Estimation and Simulation of Fractal Stochastic Point Processes," Fractals 3, 183-210 (1995).

R. G. Turcott, P. D. R. Barker, and M. C. Teich, "Long-Duration Correlation in the Sequence of Action Potentials in an Insect Visual Interneuron," J. Statist. Comput. Simul. 52, 253-271 (1995).

W. J. McGill and M. C. Teich, "Alerting Signals and Detection in a Sensory Network," J. Math. Psychol. 39, 146-163 (1995).

A. Joobeur, B. E. A. Saleh, T. S. Larchuk, and M. C. Teich, "Coherence Properties of Entangled Light Beams Generated by Parametric Down-Conversion: Theory and Experiment," Phys. Rev. A 53, 4360-4371 (1996).

C. Heneghan, S. B. Lowen, and M. C. Teich, "Two-Dimensional Fractional Brownian Motion: Wavelet Analysis and Synthesis," in Proc. IEEE Southwest Symp. Image Analysis Interpretation (San Antonio, TX, 1996), pp. 213-217.

M. C. Teich, C. Heneghan, S. B. Lowen, and R. G. Turcott, "Estimating the Fractal Exponent of Point Processes in Biological Systems Using Wavelet- and Fourier-Transform Methods," in

Wavelets in Medicine and Biology, edited by A. Aldroubi and M. Unser (CRC Press, Boca Raton, 1996), ch. 14, pp. 383-412.

C. Heneghan, S. B. Lowen, and M. C. Teich, "Wavelet Analysis for Estimating the Fractal Properties of Neural Firing Patterns," in *Computational Neuroscience*, edited by J. M. Bower (Academic, San Diego, 1996), pp. 441-446.

I. P. Herman, S. Kim, J. A. Tuchman, O. J. Glembocki, and R. S. Sillmon, "Polarized Optical Spectroscopy in InGaP Ordered Alloys under Hydrostatic Pressure," Bull. Am. Phys. Soc. 39, 86 (1994).

S. Kim, I. P. Herman, J. Bevk, and D. Hall, "Hydrostatic Pressure Dependence of Isoelectronic Bound Exciton Photoluminescence in Beryllium-doped Bulk Si and SiGe/Si Superlattices," Bull. Am. Phys. Soc. 39, 272 (1994).

I. P. Herman, "Raman Scattering," contribution to the Encyclopedia of Applied Physics, VCH Publishers, NY, vol. 15, p. 587 (1996). (no explicit sponsorhip could be cited).

S. Kim, I. P. Herman, J. A. Tuchman, K. Doverspike, L. B. Rowland, and D. K. Gaskill, "Photoluminescence Spectra in Wurtzite GaN under Hydrostatic Pressure," Bull. Am. Phys. Soc. 40, 415 (1995).

R. Eryigit and I. P. Herman, "Strain-Dependent Phonon Properties of Group IV and III-V Semiconductors," Bull. Am. Phys. Soc. 40, 808 (1995).

I. P. Herman, S. Kim, J. Bevk, and D. Hall, "Hydrostatic Pressure Dependence of Isoelectronic Bound Exciton Photoluminescence in Beryllium-doped $Si_{0.92}Ge_{0.08}$ Alloy Films and Heterostructures," Bull. Am. Phys. Soc. 40, 396 (1995).

R. Eryigit, Z. Sui and I. P. Herman, "Lattice Properties of Ge and GaAs Strained-Layers on Si," Mat. Res. Soc. Symp. Proc. 356, 295 (1995).

S. Kim, I. P. Herman, J. A. Tuchman, K. Doverspike, L. B. Rowland, and D. K. Gaskill, "Photoluminescence from Wurtzite GaN under Hydrostatic Pressure," Appl. Phys. Lett. 67, 380 (1995).

I. P. Herman, "Optical Thermometry during Semiconductor Processing," invited paper to J. Selected Topics in Quantum Electronics 1, 1047 (1995).

S. Kim, I. P. Herman, K. Moore, D. G. Hall, and J. Bevk, "Use of Hydrostatic Pressure to Resolve Phonon Replicalike Features in the Photoluminescence Spectrum of Beryllium-doped Silicon," Phys. Rev. B 52, 16309 (1995).

R. Eryigit and I. P. Herman, "Lattice Properties of Strained GaAs and Ge Using a Modified Bond Charge Model," Phys. Rev. B 53, 7775 (1996).

S. Kim, I. P. Herman, K. L. Moore, D. G. Hall, and J. Bevk, "Hydrostatic Pressure Dependence of Isoelectronic Bound Excitons in Beryllium-doped Silicon," Phys. Rev. B 53, 4434 (1996).

G. Chang, S. Kim, I. P. Herman, J. E. Spanier, D. R. Goldstein, and A. D. Kurtz, "Raman Scattering, Photoluminescence, and Transmission Spectra of porous p-type 6H-SiC," Bull. Am. Phys. Soc. 41 (1), 420 (1996).

S. Kim, G. Chang, I. P. Herman, J. Bevk, K. L. Moore, and D. G. Hall, "Isoelectronic Bound Exciton Photoluminescence in Beryllium-Doped $Si_{0.92}Ge_{0.08}$/Si Superlattices at Elevated Pressure," Bull. Am. Phys. Soc. 41 (1), 614 (1996).

J. Eng, H. Fang, C. Su, S. Vemuri, I. P. Herman, and B. E. Bent, "Real-Time Monitoring of GaAs(100) Etching by Surface Photoabsorption," Mat. Res. Soc. Symp. Proc. 309, 151 (1996).

R. Eryigit, P. K. Marschel, and I. P. Herman, "Use of Surface Photoabsorption to Analyze the Optical Response of GaAs(001) Surfaces," J. Vac. Sci. Technol. A 15, 138 (1997).

S. Kim, G. Chang, I. P. Herman, J. Bevk, K. Moore, and D. G. Hall, "Isoelectronic Bound Exciton Photoluminescence in Strained Beryllium-Doped $Si_{0.92}Ge_{0.08}$ Epilayers and $Si_{0.92}Ge_{0.08}$/Si Superlattices at Ambient and Elevated Hydrostatic Pressure," Phys. Rev. B 55, 7130 (1997).

J. E. Spanier, G. S. Cargill III, I. P. Herman, S. Kim, D. R. Goldstein, A. D. Kurtz, and B. Z. Weiss, "Effects of Nanocrystalline Structure and Passivation on the Photoluminescent Properties of Porous Silicon Carbide," Mat. Res. Soc. Symp. Proc 452, 491 (1997).

Q. Y. Yang, W. N. Schwarz, P. J. Lasky, S. C. Hood, N. L. Loo and R. M. Osgood, Jr., "Highly Anisotropic Angular Dependence of CH(3) Fragmentation from Electron-Transfer Reactions on CH(3)Br/GaAs(110)," 72, 3068 (1994).

A. Villeneuve, C. C. Yang, G. I. Stegeman, C. N. Ironside, G. Scelsi and R. M. Osgood, Jr., "Nonlinear Absorption in a GaAs Waveguide Just Above Half the Band Gap," IEEE Journal of Quantum Electronics 30, 1172 (1994).

M. B. Freiler, M. C. Shih, S. Kim, M. Levy, I. P. Herman, R. Scarmozzino and R. M. Osgood, Jr., "Pattern Transfer and Photoluminescence Damage Assessment of Deep-Submicrometer Features Etched by Photon-Induced Cryoetching," Appl. Phys. A 63, 143 (1996).

M. B. Freiler, G. F. McLane, S. Kim, M. Levy, R. Scarmozzino, I. P. Herman, and R. M. Osgood, Jr., "Luminescence Properties of Submicron Features Fabricated by using Magnetron Reactive Ion Etching with Different Sample Biases," Appl. Phys. Lett. 67, 3883 (1995).

V. Bulovic, B. Quiniou and R.M. Osgood, Jr., "Image-Potential-Induced Resonances on Al(111) Observed by Two-Photon Photoemission," J. Vac. Sci Technol. A 12, 2201 (1994).

M. C. Shih, M. B. Freiler, R. Scarmozzino, and R. M. Osgood, Jr., "Patterned, Photon-Driven Cryoetching of GaAs and AlGaAs," J. Vac. Sci. Technol. B 13, 1 (1995).

M. C. Shih, M. Hu, M. B. Freiler, M. Levy, R. Scarmozzino, R. M. Osgood, Jr., I. W. Tao, and W. I. Wang, "Fabrication of an InGaA in SQW Circular Ring Laser by Direct Laser Patterning," Appl. Phys. Lett. 66, 2608 (1995).

X. Y. Wang, R. Paiella, and R. M. Osgood, Jr., "Two-Dimensional Electron Scattering Processes on Na-Dosed Cu(111): A Two-Photon Photoemission Study," Phys. Rev. B 51, 17035 (1995).

J.-L. Lin, M. B. Freiler, M. Levy, D. Collins, T. C. McGill, and R. M.Osgood, Jr., "Photon-Assisted Cryoetching of III-V Binary Compounds by C12 at 193 nm," Appl. Phys. Lett. 67, 3563 (1995).

P. J. Lasky, P. H. Lu, X. Y. Wang, R. M. Osgood Jr., B. E. Bent, and P. A. Stevens, "NEXAFS Measurements Indicating a Tilted Molecular Orientation for Methyl Halides on GaAs(110)," Surf. Sci. 336, 140 (1995).

X. Y. Wang, X. J. Shen, R. M. Osgood Jr., R. Haight, and F. J. Himpsel, "Observation of Lateral Superlattice Effects on Stepped Cu(001)," Phys. Rev. B 53, 15 738 (1996).

P. H. Lu, P. J. Lasky, Q. Y. Yang and R. M. Osgood Jr., "Dynamics of Hot-Electron Transfer in Oriented Methyl Halides on GaAs(110)," Chem. Phys. (special issue on "Surface Reaction Dynamics") 205, 143 (1996).

L. L. Chao, M. B. Freiler, M. Levy, J. L. Lin, G. S. Cargill III, R. M. Osgood Jr. and G. F. McLane, "Cathodoluminescence Study of Diffusion Length and Surface Recombination Velocity in III-V Multiple Quantum Well Structures," Mat. Res. Soc. Symp. Proc. 406, 543 (1996).

L.-L. Chao, G. S. Cargill III, M. Levy, R. M. Osgood, Jr., and G. F. McLane, "Cathodoluminescence Study of GaAs Quantum Wells and of Submicron Dots Fabricated by Magnetron Reactive Ion Etching," Appl. Phys. Letts. 70, 408 (1997).

R. M. Osgood, Jr. and X. Y. Wang, "Image States on Single-Crystal Metal Surfaces," Chapter in *Solid State Physics* , H. Ehrenreich and F. Spaepen, eds., (Academic Press, 1997).

C.-K. Ni, G. W. Flynn, and S. Green, "Experimental and Theoretical Velocity Profiles for Pure Rotational Scattering: CO-Hot Hydrogen Atom Collisions," J. Chem. Phys. 101, 9499 (1994).

D. R. Willey, K. A. Ross, A. S. Mullin, S. Schowen, L. Zheng, and G. Flynn, "Gas-phase Infrared Spectroscopy of N_2O in an Equilibrium Cell at 10 and 5 K," J. Mole. Spec. 169, 66-72 (1995).

R. E. Weston, Jr. and G. W. Flynn, "Collisional Energy Transfer from Hot Atoms to Small Molecules," *Advances in Chemical Kinetics and Dynamics* 2B, 359-391 (1995); John Barker, Ed.; JAI Press Inc., Greenwich, CT.

G. W. Flynn and R. E. Weston, Jr., "Glimpses of a Mechanism for Quenching Unimolecular Reactions: A Quantum State Resolved Picture," *Advances in Chemical Kinetics and Dynamics* 2A, 75-107 (1995); John Barker, Ed.; JAI Press Inc., Greenwich, CT.

B. Venkataraman, J. J. Breen, and G. W. Flynn, "Scanning Tunneling Microscopy Studies of Alcohol/Alkane Mixtures Adsorbed on Graphite Surfaces," in *Atomic Force*

Microscopy/Scanning Tunneling Microscopy, page 117, Plenum, New York, 1994, Eds. S. H. Cohen, M. T. Bray, and M. L. Lightbody (Proc. US Army, Natick Conf. on Force Microscopy, 1993).

B. Venkataraman, J. J. Breen, and G. W. Flynn, "STM Studies of Solvent Effects on the Adsorption and Mobility of Triacontane/Triacontanol Molecules Adsorbed on Graphite," J. Phys. Chem. 99, 6608 (1995).

C.-K. Ni, T. G. Kreutz and G. W. Flynn, "Experimental and Theoretical Velocity Profiles for Pure Rotational Scattering in CO_2-Hot Hydrogen Atom Collisions," J. Phys. Chem. 99, 7381 (1995).

A. S. Mullin, C. A. Michaels, and G. W. Flynn, "Molecular Supercollisions: Evidence for Large Energy Transfer in the Collisional Relaxation of Highly Vibrationally Excited Pyrazine by CO_2," J. Chem. Phys. 102, 6032 (1995).

C. A. Michaels, A. S. Mullin, and G. W. Flynn, "Long and Short Range Interactions in the Temperature Dependent Collisional Excitation of the Anti-symmetric Stretching $CO_2(00^01)$ Level by Highly Vibrationally Excited Pyrazine," J. Chem. Phys. 102, 6682 (1995).

B. Venkataraman, G. W. Flynn, J. Wilbur, J. Folkers, and G. Whitesides, "Differentiating Functional Groups with the Scanning Tunneling Microscope," J. Phys. Chem. 99, 8684 (1995).

C. Michaels, C. Tapalian, Z. Lin, E. Sevy, and G. Flynn, "Supercollisions, Photofragmentation, and Energy Transfer in Mixtures of Pyrazine and Carbon Dioxide," Faraday Disc. 102, 405-22, (1995), *Unimolecular Reaction Dynamics*.

L. M. Struck, J. Eng, B. E. Bent, Y. J. Chabal, G. P. Williams, A. E. White, S. Christman, E. E. Chaban, G. W. Flynn, K. Radermacher and S. Mantl, "Silicon Surface Chemistry by IR Spectroscopy in the Mid to Far IR Region: Water and Ethanol on Si(100)," Mat. Res. Soc. Symp. Proc. 386, 395 (1995).

D. M. Cyr, B. Venkataraman, and G. W. Flynn, "STM Investigations of Organic Molecules Physisorbed at the Liquid-solid Interface", Chemistry of Materials; Nanostructured Materials 8, 1616 (1996).

D. Cyr, B. Venkataraman, G. W. Flynn, A. Black and G. Whitesides, "Functional Group Identification in Scanning Tunneling Microscopy of Molecular Adsorbates", J. Phys. Chem. 100, 13747 (1996).

G. W. Flynn, C. S. Parmenter, and A. M. Wodtke, "Vibrational Energy Transfer", J. Phys. Chem. 100, 12817 (1996), (Centennial Issue).

L. M. Struck, J. Eng, Jr., B. E. Bent, G. W. Flynn, Y. J. Chabal, S. Christman, G. P. Williams, K. Radermacher and S. Mantl, "Silicon Surface Chemistry by IR Spectroscopy in the Mid- to Far-IR Region: Water and Ethanol on Si(100)", Mat. Res. Soc. Symp. Proc. 386, 395-400 (1995).

B. Venkataraman and G. W. Flynn, "Scanning Tunneling Microscopy Studies of Hydrocarbons Adsorbed on Graphite Surfaces", in "Atomic Force Microscopy/Scanning Tunneling Microscopy", in press, Proc.U. S. Army, Natick Conference on Scanning Force Microscopy, Plenum, New York, 1996, Eds. S. H. Cohen, M. T. Bray, and M. L. Lightbody.

M. X. Yang, J. Eng, Jr., P. W. Kash, G. W. Flynn, B. E. Bent, M. T. Holbrook, S. R. Bare, J. L. Gland, and D. A. Fischer "Generation and Reaction of Vinyl Groups on a Cu(100) Surface", J. Phys. Chem., 100, 12431-12439 (1996)

P. W. Kash, D.-H. Sun, M. Xi, G. W. Flynn, and B. E. Bent, "Cross Coupling of Phenyl Groups with Alkyl Iodides on a Cu(100) surface: A Radical Mechanism?", J. Phys. Chem., 100, 16, 621-16,628 (1996)

L.-L. Chao, G. S. Cargill, III, C. Kothandaraman, D. Cyr, G. Flynn, and E. Hellman, "Nonuniform Morphology and Luminescence Properties of an MBE GaN Film by AFM, SEM and Cathodoluminescence", MRS Internet J. Nitride Semiconductor Res., http://nsr.mij.mrs.org/2/7/

H. C. Tapalian, C. A. Michaels and G. W. Flynn, "Mid-Infrared Molecular Gas Lasers Optically Pumped by a Continuously Tunable IR Optical Parametric Oscillator", Appl. Phys. Letts., 70, 2215-17 (1997)

C. A. Michaels and G. W. Flynn, "Connecting Scattering Data Directly to Chemical Kinetics: Energy Transfer Distribution Functions for the Collisional Relaxation of Highly Vibrationally Excited Molecules from State Resolved Probes of the Bath", J. Chem. Phys. 106, 3558-3566 (1997)

C. A. Michaels, Z. Lin, A. S. Mullin, H. C. Tapalian, and G. W. Flynn, "Translational and Rotational Excitation of the $CO_2(00^00)$ Vibrationless State in the Collisional Quenching of Highly Vibrationally Excited Perfluorobenzene: Evidence for Impulsive Collisions Accompanied by Large Energy Transfers", J. Chem. Phys. 106, 7055-7071 (1997)

G. W. Flynn, C. A. Michaels, H. C. Tapalian, Z. Lin, E. Sevy, and M. A. Muyskens"Infrared Laser Snapshots: Vibrational, Rotational, and Translational Energy Probes of High Energy Collision Dynamics", in *Highly Excited States: Relaxation, Reaction, and Structure*, ACS Books, Eds. Amy Mullin and George Schatz, accepted for publication.

Leanna Giancarlo, Donna Cyr, Karen Muyskens, and George W. Flynn, "Scanning Tunneling Microscopy of Molecular Adsorbates at the Liquid/Solid Interface: Functional Group Variation in Image Contrast", submitted for publication

P. W. Kash, M. X. Yang, A. V. Teplyakov, G. W. Flynn and B. E. Bent, "Chemical Displacement of Molecules Adsorbed on Copper Surfaces: Low Temperature Studies with Applications to Surface Reactions", submitted for publication.

C. Su, Z.-G. Dai, D.-H. Sun, W. Luo, M. Vernon, and B. E. Bent, "Chemical Dry Etching of GaAs by HCl: Products, Rate, and a Kinetic Model," *Surf. Sci.* 312, 181-197 (1994).

C. Su, Z.-G. Dai, H.-Q. Hou, M. Xi, M. F. Vernon, and B. E. Bent, "GaAs Etching by Cl_2 and HCl: Ga- vs. As-Limited Etching," Mat. Res. Soc. Symp. Proc. 334, 413-418 (1994).

P. J. Lasky, P. H. Lu, M. X. Yang, R. M. Osgood, Jr., B. E. Bent, and P. A. Stevens, "NEXAFS Measurements Indicating a Tilted Molecular Orientation for Methyl Halides on GaAs(110)," Surf. Sci. 336, 140-148 (1995).

A. V. Teplyakov and B. E. Bent, "Distinguishing Direct and Quasi-direct Mechanisms for an Eley-Rideal Gas/Surface Reaction," J. Chem. Soc. Faraday Trans. 91, 3645 (1995).

B. E. Bent, "Mimicking Aspects of Heterogeneous Catalysis: Generating, Isolating and Reacting Proposed Surface Intermediates on Single Crystals in Vacuum," Chem. Rev. 96, 1361 (1996).

Y. F. Yang, W. I. Wang and E. S. Yang, "State Holding Circuit Using HBTs RTDs," Electron Lett. 30, 90 (1994).

Y. F. Yang, C. C. Hsu and E. S. Yang, "Surface Recombination Current in InGaP/GaAs Hetero-Emitter Bipolar Transistors," IEEE Trans. Electron Devices 41, 643 (1994).

P. W. Li, E. S. Yang, Y. F. Yang, J. Chu, and B. Meyerson, "SiGe p-channel MOSFETs with a Gate Oxide Fabricated by Electron Cyclotron Resonance Microwave Plasma Processing," IEEE Elec. Dev. Lett. 15, 402 (1994).

P. W. Li, E. S. Yang and Y. F. Yang, "Electron Cyclotron Resonance Microwave Plasma Enhanced SiGe Oxidation and MOS Transistor," Proc. 21st Int. Symp. on Compound Semiconductor (1994).

Y. F. Yang, C. C. Hsu, and E. S. Yang, "A Pseudomorphic $Ga_{0.2}In_{0.8}P/Ga_{0.47}I_{0.53}As/InP$ HEMT Grown by MOVPE Using IBP and TBA," Electronic Letters 30, 1894 (1994).

Y. F. Yang, C. C. Hsu, Y. K. Chen and E. S. Yang, "Comparison of GaInP/GaAs heterostructure-emitter bipolar transistors and heterojunction bipolar transistors," IEEE Trans. Electron Devices 42, 1210 (1995).

Y. F. Yang, C. C. Hsu and E. S. Yang, "Carbon-doped GaInP/GaAs double heterostructure-emitter bipolar transistor with high current gain," IEEE Trans. Electron Devices 42, 1386 (1995).

W. Xin, H. K. Liou, E. S. Yang, L. Xu and S. H. Xin, "Picosecond carrier life time in relaxed silicon germanium and low temperature gallium arsenide," Bulletin of The American Physical Society 40, 802 (1995).

S. H. Hong, J. R. Miller, Q. Y. Ma, E. S. Yang and G. M. Luke, "Inhibition of superconductivity in YBaCuO films by Aluminum ion implantation," Appl. Phys. Lett. 67, 2717 (1995).

S. H. Hong, J. R. Miller, Q. Y. Ma and E. S. Yang, "Modification of epitaxial oxide films with ion implantation doping," Proc. MRS Fall Meeting (November 1995).

Y. F. Yang, C. C. Hsu, and E. S. Yang, "Effects of emitter set-back layer thickness on the performance of GaInP/GaAs heterostructure-emitter bipolar transistors," In the Proceeding of the 1995 Int'l. Semiconductor Device Research Symposium, Charlottesville, VA, p.151 (December 1995).

Y. F. Yang, C. C. Hsu, and E. S. Yang, "High Frequency and low noise C-doped GaInP/GaAs heterojunction bipolar transistor grown by MOCVD using TBA and TBP," Electronics Lett. 32 689 (1996).

Y. F. Yang, C. C. Hsu, and E. S. Yang, "Integration of GaInP/GaAs heterojunction bipolar transistors and high electron mobility transistors," IEEE Electron Device Lett. 17, 363 (1996).

Y. F. Yang, C. C. Hsu, and E. S. Yang, "A GaInP/GaAs HBT with a selective buried sub-collector layer grown by MOCVD," Proc. 54th Devices Research Conference, Santa Barbara, CA, p.34 (June 1996).

C. C. Hsu, Y. F. Yang, H. J. Ou, and E. S. Yang, "CCl_4-doped Semi-insulating InP as Buffer Layer in GaInP/InP High Electron Mobility Transistors," Appl. Phys. Lett. 69, (8), (August 1996).

E. INVENTIONS

E. S. Yang with Yuefi Yang, "Fabrication of GaAs HBTs using a Buried Selective Sub-collector Layer," patent pending. (Invention Report Form 882 dated 4/17/96)

G. W. Flynn, "Molecular Gas Laser Pumped by an Infrared Optical Parametric Oscillator," (Invention Report Form 882 Dated 10/15/96).